Published by Associazione Teriologica Italiana
Hystrix, the Italian Journal of Mammalogy
Online first – 2022
OPEN ACCESS
Available online at:
http://www.italian-journal-of-mammalogy.it
doi:10.4404/hystrix-00534-2022

Commentary

Priorities and gaps in Mediterranean bat research evidence: a systematic review for the early twenty-first century

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Keywords:
systematic review
ecology
Mediterranean basin
conservation
Chiroptera
bat activity

Article history:
Received: 11 March 2022
Accepted: 07 July 2022

Acknowledgements
We dedicate this work to Prof. Bruno Massa in recognition of all his contribution. This study was supported by Ph.D. program scholarship by Palermo University. We thank the two anonymous reviewers for their useful comments and suggestions that have improved this manuscript.

Abstract

Bat conservation is one of the top global concerns for research today; however, conservation efforts may still be limited and impotent due to inadequacy and scarcity of data. Hence, identifying research trends, threatening factors, species status, and geographical priorities is an essential tool for future conservation, protection and prioritization. Here we conduct a comprehensive systematic review to identify current research priorities, trends, general patterns and gaps regarding Mediterranean bat researches. A total of 97 studies were found in the years spanning between 2000 and 2021. There were 18 studies with sufficient data for qualitative statistical analysis to investigate the impact of different habitat and land managements on bat activity and species richness. A yearly average of 4.6 articles were published, with a slight increase post-2010. Out of 61 identified species, 21% of species are threatened. Approximately, 65% of studies were conducted in the Mediterranean European region, primarily in Spain (29%), Italy (15.5%), and Portugal (10.3%), largely focusing on forest habitats (38%). We found that Mediterranean bat species received uneven research attention, with only 15% of research allocated to threatened bats. Around half of the studies focused on the following bat species; *Pipistrellus pipistrellus*, *Pipistrellus kuhlii*, *Miniopterus schreibersii*, *Rhinolophus hipposideros*, *Pipistrellus pygmaeus*, *Myotis myotis*, and *Rhinolophus ferrumequinum*. Our statistical analysis showed that riparian areas had higher bat activity than forest and agriculture areas. Bat population responded positively to forest management and organic agriculture practices. To reduce future research misalignment between current local research status and future global conservation priorities, we strongly advocate for urgent and additional collaborative efforts to target under-researched species and areas. Finally, our review will provide a general overview and an objective synthesis on the current status of bats in the Mediterranean and serve as a baseline for further effective research.

Introduction

Bats are the world's second-largest mammals group, with over 1440 species (Mammal Diversity Database, 2020). They provide a wide range of ecological services, including being natural insect predators for a copious amount of insects, particularly arthropods (Puig-Montserrat et al., 2020; Williams-Guillén et al., 2016; Boyles et al., 2011), seed dispersals, in addition to being well known as fruit pollinators for several highly economic valued fruits (Florens et al., 2017). They are also well recognized as an excellent bio-indicator to anthropogenic and environmental changes (Russo et al., 2021). Today, billions of dollars per year is the estimate of bat's economic contributions (Korine et al., 2020; Puig-Montserrat et al., 2015; Kunz et al., 2011). Despite their numerous benefits to the ecosystem, several bat species are experiencing populations decline, and 15% are classified as endangered species (IUCN, 2021). The proportion of threatened bats is expected to rise in many regions, including the Mediterranean basin, where conservation efforts and research are still inadequate (Voigt and Kingston, 2016; De Paz et al., 2015).

The Mediterranean landscape supports a moderately speciose diversity of 61 bat species belonging to eight different families (IUCN, 2021). More than 95% of Mediterranean species are insectivores. There are at least seven endemic species, including *Rhinolophus euryale*, known as the Mediterranean horseshoe bat. The majority of Mediterranean bats rely on the forest and natural habitats (Georgiakakis et al., 2018). According to the International Union for Conservation of Nature (IUCN), 21 bat species are currently experiencing population trend declines on the Mediterranean scale caused by environmental and anthropogenic factors (O'Shea et al., 2016). In this regard, forest loss and fragmentation pose a pervasive threatening impact on bat survival (Lison and Calvo, 2014). The overuse of chemicals in agriculture is leading to a decline of insect population, therefore reduction of bat food availability (Oliveira et al., 2020). Bats are also impacted by urbanization, wind farms, water pollution, road effects, and climate change (Bideguren et al., 2019; Russo and Ancillotto, 2015; Amorim et al., 2012). However, some factors such as forest management and agricultural practices impact and implications on bat activity and population assemblages are still ambiguous and controversial (Froidevaux et al., 2021; Bender et al., 2015). In several cases bat populations showed positive reactions and benefited from forest management (Law et al., 2016; Russo et al., 2010). Agriculture practices, on the other hand, were discovered to have a mixed impact on bat activity and species richness (Puig-Montserrat et al., 2015). All of these factors, combined with the erratic response of bats, compel us to take urgent actions with the ongoing changes that may pose undesirable effects on Mediterranean bat populations (Jung and Threlfall , 2016).

Although the global increase in number of researchs targeting bats conservation (Frick et al., 2019), research and knowledge about Medi-

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terranean bats are still scattered, making it difficult to fully understand the current status of bats. Mediterranean basin was barely addressed as a discrete region. In fact, the most recent report assessing the Mediterranean bats was detailed by the IUCN in 2009. Therefore, identifying main stressing factors, population trends, in addition to understanding ongoing research priorities, are considered an essential step for bat conservation on a national and regional scale. Intuitively, research efforts varies across species, countries, and thematic areas over the years. Hence, updated information on species based on past and current research are paramount to prioritizing future conservation targets.

In this comprehensive review, we synthesise the breadth of our knowledge on Mediterranean bat species and quantify recent information regarding population, species and research trends, knowledge gaps, and threatening factor. Through statistical approach analysis, we also aim to assess the impact of different types of habitats and land management on bat activity and species richness. Supported with previous studies, we anticipate to evaluate topics and species priorities over the last 20 years. Finally, this paper will effectively provide an overview of the Mediterranean bat status and serve as a solid directional baseline for future studies with the aim of conservation.

Materials and methods

Review data research method

A systematic review was carried out between July 20th and July 30th, 2021 (Fig. 1), using the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) protocol (Moher et al., 2009). The temporal window of the researched papers was bounded between the years 2000 and 2021. A dataset was created based on the published literature obtained from Web of Science and Scopus using the combination of the following keywords: (Bat∗ or Chiroptera) AND (Mediterranean or Mediterranean basin). Citations from retrieved papers were also checked to ensure a broader range of dataset patterns. Except for the IUCN report, grey literature, thesis, and technical reports were not included. Following the combination of papers from the research sources, a primary scanning was done by sequentially reviewing the title and the abstract of the article, or the whole article, if necessary. Then, a full-text scanning and evaluation were performed.

A total of 97 articles were included and subjected to full-text scanning. Papers were classified based on their target research habitats; forest (1), agricultural area (2), caves (3), labs (4), riparian area (5), multi-areas (6), urban area (7), Sahara (8) and not indicated (9). Furthermore, each paper was assigned to a specific thematic research topic generally deduced from the paper's aim. Papers were later standardized and classified into the following five main thematic research topics; "Conservation", "Disease", "Ecology", "Taxonomy" and "Species records" (Tab. 1). Also, the following information were extracted from each paper: the year of publication, the author and location of the study, target habitats, threating factors, studied species, and the methodology applied in each study (e.g. morphology, molecular, acoustic monitoring, isotopic analysis, radio-tracking, observation and mist netting).

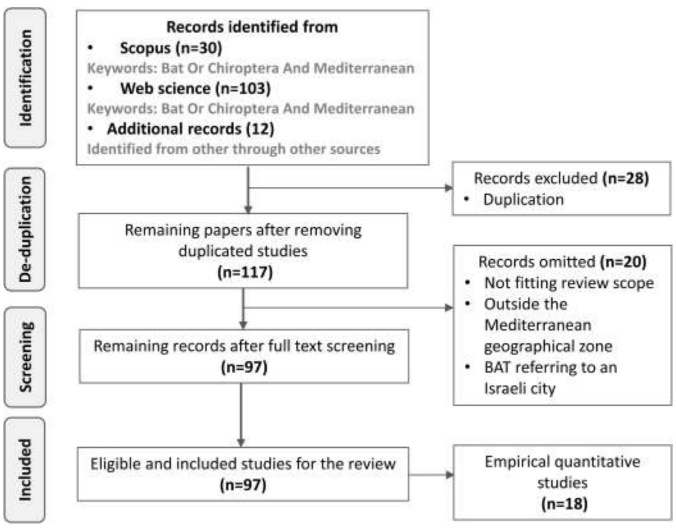

Figure 1 – Flowchart of the systematic research strategy followed, displaying the steps taken and the number of included and excluded articles, as well as the criteria used to select the eligible articles for this review (PRISMA by Moher et al., 2009).

For quantitative analysis, we used a total of 18 studies incorporating empirical acoustic datasets reporting bat activity and species richness. Acoustic data was used as it was the most readily accessible and comparable data form. All extracted acoustic data, with the exception of the Barros et al. (2017), were collected during the summer season. All 18 studies were conducted in at least one of three habitats: forest, riparian, or agricultural. Forest and agriculture studies were divided into two subgroups: managed and unmanaged forests, and organic and traditional agriculture, respectively. For each of the study sites, we extracted the following environmental variables: mean annual precipitation (mm) and mean altitude (m a.s.l). We obtained environmental data from other publications or weather websites (www.wunderground.com) when information was missing.

Species status and threats

To assess the current status of bat species in the Mediterranean, we categorized all cited species into subgroups based on the most recent IUCN red list status. All species classified as data deficient (DD), vulnerable (VU), and endangered (EN) were considered "threatened" species, whereas species identified as least concern (LC) or near threatened (NT) were deemed as "non-threatened" species. Supplementary information on the species were obtained from the IUCN website, such as family, types of foraging, natural habitats, and their geographical distribution across the basin. Due to the various type of threats mentioned in the papers, threats were grouped into nine major groups based on the IUCN list (Tab. 1). Each threat group comprised several subthreats. For instance, forest disturbance group includes fires, forest managements- logging and snag cutting.

Data analysis

The distribution of the number of publications per thematic research groups (Conservation, Ecology, Disease, Taxonomy and Species records), species taxa, species families, species status (threatened and non-threatened) and per study location (Africa, Europe and Asia) were tested using Pearson's Chi-square independence test (χ^2). For the quantitative statistical analysis, we extracted the mean bat activity, the number of species identified acoustically, and the sample size, which was the number of study sites for the majority of the papers. Then, all mean bat activities were standardized into (bat passes/min) and were log-transformed to achieve normality. A one-way ANOVA followed by a Tukey-Kramer post hoc test was used to determine whether there were any significant differences in bat activity between different types of habitats (agriculture, forest, riparian), as well as between forest management (managed forest, unmanaged forest) and agricultural practices (organic agriculture, conventional agriculture). Generalized Linear Models (GLM) using Poisson distribution was performed to assess the influence of different habitat variables and environmental variables (precipitation and altitude) on species richness and bat activity. All statistical analysis and plots were carried out with R version 4.1.2 (R Core Team, 2021) using `ggplot2` and `lme4` packages.

Results

Research topic trends over the last 21 years

A total of 97 papers published between 2000 and 2021 were included, with an average of 4.6 articles per year (Fig. 2). A higher number of papers was published between the year 2010 to 2021 (μ=5.8 articles/year), compared to an average of 3.4 articles between 2000 and 2010 (Fig. 2). The highest number of papers published in a single year was nine (in 2007), while only one article was published in 2004 and 2005, respectively. According to the distribution of studies among the five main

Table 1 – Description of the primary and secondary thematic research topics, as well as main and sub-threat categories (adapted from Preble et al., 2021).

Main Thematic research	Secondary thematic research	Key contents
Conservation	Threats – Conservation plans	Studies with conservation goals. Including studies related to threats, human-bat interactions, conservations strategies.
Disease	Virus – parasites	Involve studies concerning viruses (Lyssavirus), parasites (trombiculids) – insular syndromes.
Ecology	Foraging – roosting – ecosystem role – niche modelling – paleoecology – reproductive ecology	Studies dealing with ecosystem role of bats, habitat selection and foraging sites, bat behaviour, migration diet, isotopes and guano analysis and niche modelling.
Species records	Checklists – community composition – palaeontology – species descriptions	Includes mainly species descriptions and species records and compositions in a specific study area using monitoring techniques (observation, acoustic identifications, mist netting. etc.)
Taxonomy	Morphological analysis – phylogenetics – paleontology	Phylogenetic and morphological research (wing, anatomical morphology) and histological studies aiming to describe bat species taxonomy, in addition to specify phenotypic and genetic traits, as well as the differentiation of new cryptic species.
Threats	**Subgroups**	**Description**
Agriculture	Chemical pesticides	Agricultural practices, particularly the overuse of chemical pesticides, which may result in the loss of bat food sources.
Climate change	Temperature change – global warming	It has a considerable impact on roost temperatures and may also affect hibernation periods, as well as resulting in direct mortality in cases of heat waves, intense storms, flooding, and drought.
Data deficiency	Lack of information – Understudied species	Underexplored and poorly studied species may suffer direct threats because several species may be on the verge of extinction and are not being adequately protected and monitored due to a lack of information.
Disease	Viruses – bacteria – parasites	Bat-borne zoonotic disease is regarded as a serious threat, particularly in terms of increasing their social dislike as well as directly affecting bat health in cases of parasite and bacterial contamination.
Habitat disturbance	Reconstruction – old building demolition – cave disturbance	This could result in the loss or alteration of foraging habitats and roosts especially present in old buildings.
Forest disturbance	Fires – forest managements	Forest disturbances including fires and forest managements have a negative impact on bat species richness, community structure, and particularly habitat loss.
Urbanization	Roads – light and noise pollution – reconstruction – wind farms	ausing direct mortality (for instance at wind farm sites), fragmenting habitats with roads or reducing habitat quality with artificial lightning that many bat species avoid in addition to bat disturbance (during hibernation phase) caused by reconstruction practices.
Water availability	Water pollution – water availability	Despite their exceptionally narrow water source requirements, bats are especially vulnerable when water is scarce or polluted.

thematic research topics, the "Ecology" thematic topic was found to be the most studied with 38.1% of the total papers, followed by "Species records" (24.7%), "Taxonomy" (18.5%) and "Conservation" studies (15.5%), and only three papers (3.1%) focused on "Disease" studies (Fig. 3).

Applied methods

Acoustic monitoring was the most commonly used method, with 30 out of 97 articles (Fig. 4). The "DNA analysis" was the second most cited method used in 19 studies (19.5%). "Morphology" and "radio-tracking" methods accounted for 17.2% and 15.08% of the total studies, respectively. While "excavation" (2.3%), "isotopic analysis" (3.44%),

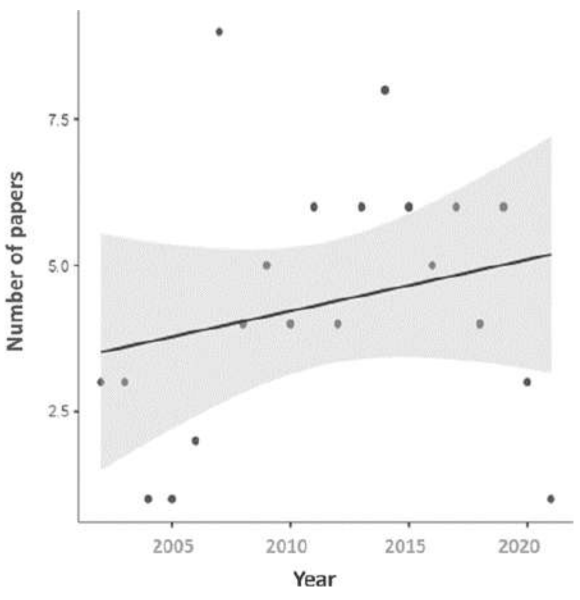

Figure 2 – Number of publications over the last 20 years (2000–2021) related to Mediterranean bats.

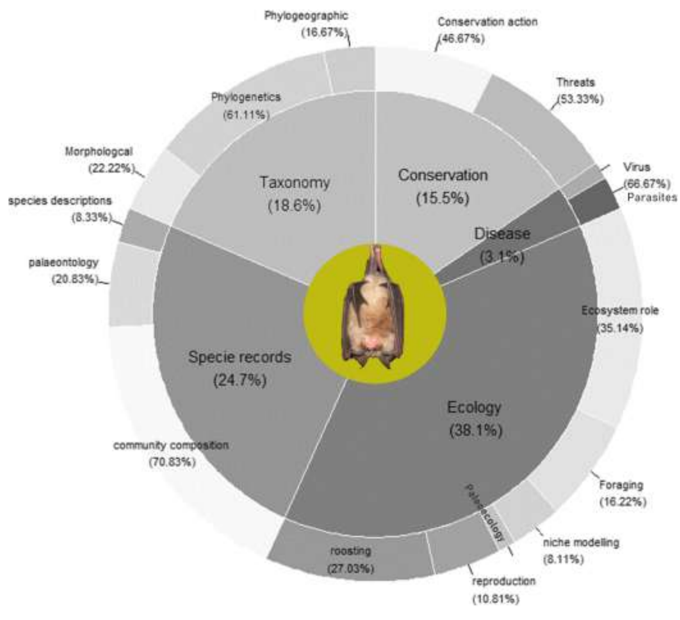

Figure 3 – The distribution of publications over the last 20 years according to their primary and secondary thematic research topics.

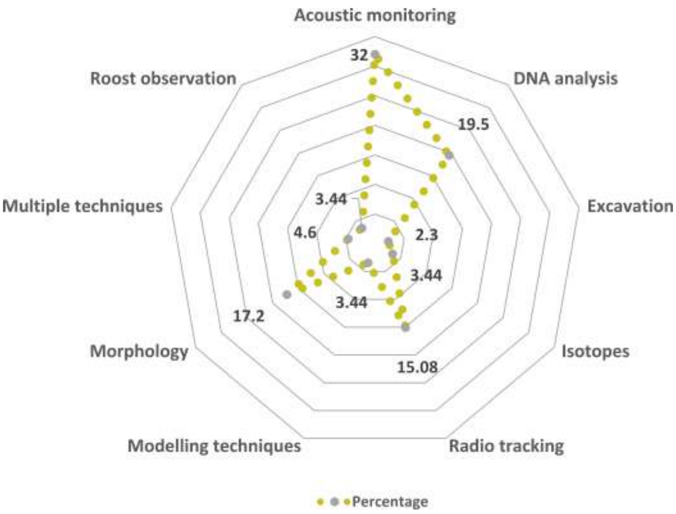

Figure 4 – The distribution of the methods used across the 97 publications.

"roost observation" (3.44%), and "modelling technique" (3.44%) were found to be less commonly used. Only 4.6% of the total studies applied "multiple techniques", through combining "morphological" and "acoustic monitoring" or "radio-tracking" – "roost observation", "radio-tracking", and "DNA analysis".

Geographical research distribution

Our findings revealed that the 97 studies were carried out in 18 different countries spread across three continents (Africa, Asia, and Europe). The number of publications was significantly higher in the Mediterranean European countries than in the Asian and African Mediterranean areas (χ^2=134.125, d.f=162, p<0.0001). Approximately 65% of studies were in the Mediterranean European part (Fig. 5A). Spain, Italy, and Portugal were the most studied countries, with 28, 15, and 10 papers, respectively (Fig. 5B).

Mediterranean Asian countries, on the other hand, accounted for only 13.4% of total papers, led primarily by Israel (n=7), followed by Turkey (n=4), and Lebanon and Syria one paper each. Nearly 12.7% of the studies were performed across several Mediterranean countries. The Mediterranean African region generated the least amount of papers, accounting for only 8.96% of total publications. Studies focused on nine different target habitats. Around 38% of the total studies (n=36) targeted Mediterranean forests followed by, caves (n=15, 15.5%), agricultural sites (n=11, 11.3%), riparian areas (n=9, 9.3%). Only six studies were conducted in labs and artificial roosts. Sahara was the least researched region with only 3% of the papers, and two studies did not specify the habitats studied. Notably, 16 papers (16.5%) covered various habitats, mainly forest, agriculture, and riparian areas.

Researched species

A total of 61 bat species belonging to eight families were listed at least once in the 97 analysed articles. Only one species of bat was identified as frugivorous (*Rousettus aegyptiacus)*, while the rest were insectivorous. A total of 21% of bat species are threatened, with 15% as vulnerable, and 6% data deficient (Fig. 6B). In terms of the number of species cited per paper, uneven distribution and a significant difference were observed ranging between 1 and 19 (χ^2=844.51, d.f.=177, p<0.0001) (excluding the IUCN report and checklists), with an average of 3.82±4.25 (mean±standard deviation) recorded species per publication. Vespertilionidae was the most cited family (n=381) (Tab. 2), followed by Rhinolophidae (n=67) and Molossidae (n=16). Other families were rarely quoted, including species belonging to Rhinopomatidae (n=9), Pteropodidae (n=7), Miniopteridae (n=2), Hipposideridae (n=2), and Emaballonuridae (n=4).

At the species level, *Pipistrellus pipistrellus*, *Pipistrellus kuhlii*, and *Miniopterus schreibersii* were the most intensively studied species found in 31% of papers, followed by *Rhinolophus hipposideros* (21.8%), *Pipistrellus pygmaeus* (20.6%), *Myotis myotis* (20.6%), and *Rhinolophus ferrumequinum* (19.54%). The remaining species were cited between three to fourteen times, whereas three species were listed only once. Threatened species received less attention, appearing in only 15% of all articles. The remaining 85% of papers focused on non-threatened species, with an average of (8±8.8) articles per species (Fig. 6B).

Main threats

Nine major threatening factors affecting the Mediterranean bat population were identified throughout the studied papers (Fig. 7). Yet around 20.6% of the total papers elicited no information on threats. Forest disturbances, such as fires and deforestation, were pointed out as the most common threatening factor with 18.3%, followed by agricultural practices, in particulary the overuse of chemical pesticides (14.8%), climate change (11.5%), water resources, such as water availability and water pollution (8%). Data deficiency was identified as a significant threatening factor in 6.8% of the papers. Disease and urbanization had a lower impact on bats, accounting for 3.4% and 4.6%, respectively.

Bat activity, species richness and environmental influence

Bat activity and species richness were assessed in three different types of habitats and four different types of land management. Overall, bat activity averaged 0.87 bat passes /min and ranged between 0.01 (olives groves) and 8.86 passes/min (rivers). As to bat species richness, species number varied between one to 19 species per study. Habitats conditions effect on bat activity and species richness varies significantly among study areas. Bats were found generally more active in riparian areas (ANOVA, F=3.67; p=0.022, α=0.05), than in forest (0.66±0.62 passes/min) (Tukey-Kramer post-hoc-test, p=0.032) and agricultural areas (0.61±0.14 passes/min) (Tukey-Kramer post-hoc-test, p=0.021), where no difference was observed between these two habitats (ANOVA, F=0.16; p=0.690, α=0.05) (Fig. 8). Also, no significant difference in bat activity was detected between managed and unmanaged forest (Tukey-Kramer post-hoc-test, p=0.726) as well as between tradition and organic agricultural (Tukey-Kramer post-hoc-test, p=0.695). Oppositely, species richness did not significantly differ among the different habitat types (riparian, forest, agriculture) (GLM, χ^2=3.43, p=0.18). However, unmanaged forests proved to have an important driver for species richness compared to manage forest areas. In agricultural habitats, bat species were found more diverse in organic agricultural fields than conventional agricultural land. In terms of environmental variables, annual precipitation had a negative effect on bat activity (t=-2.41, p=0.019) and no effect on species richness (GLM, χ^2=0.55, p=0.45). Contrary, altitude had no impact on bat activity (t=0.44, p=0.66) but influenced positively bat species composition (GLM χ^2=5.43, p=0.01).

Table 2 – Distribution of the number of species in the eight families found in the studies and their red list status based on IUCN latest classification (IUCN, 2021).

Family	Number of species	Threatened species (% threatened species)	Number of citations
Vespertilionidae	45	9 (20%)	381
Molossidae	1	0 (0%)	16
Rhinolophidae	6	3 (50%)	67
Rhinopomatidae	2	0 (0%)	9
Pteropodidae	1	1 (100%)	7
Hipposideridae	2	0 (0%)	2
Emaballonuridae	2	0 (0%)	4
Miniopteridae	2	1 (50%)	2
Total	61	13 (21%)	488

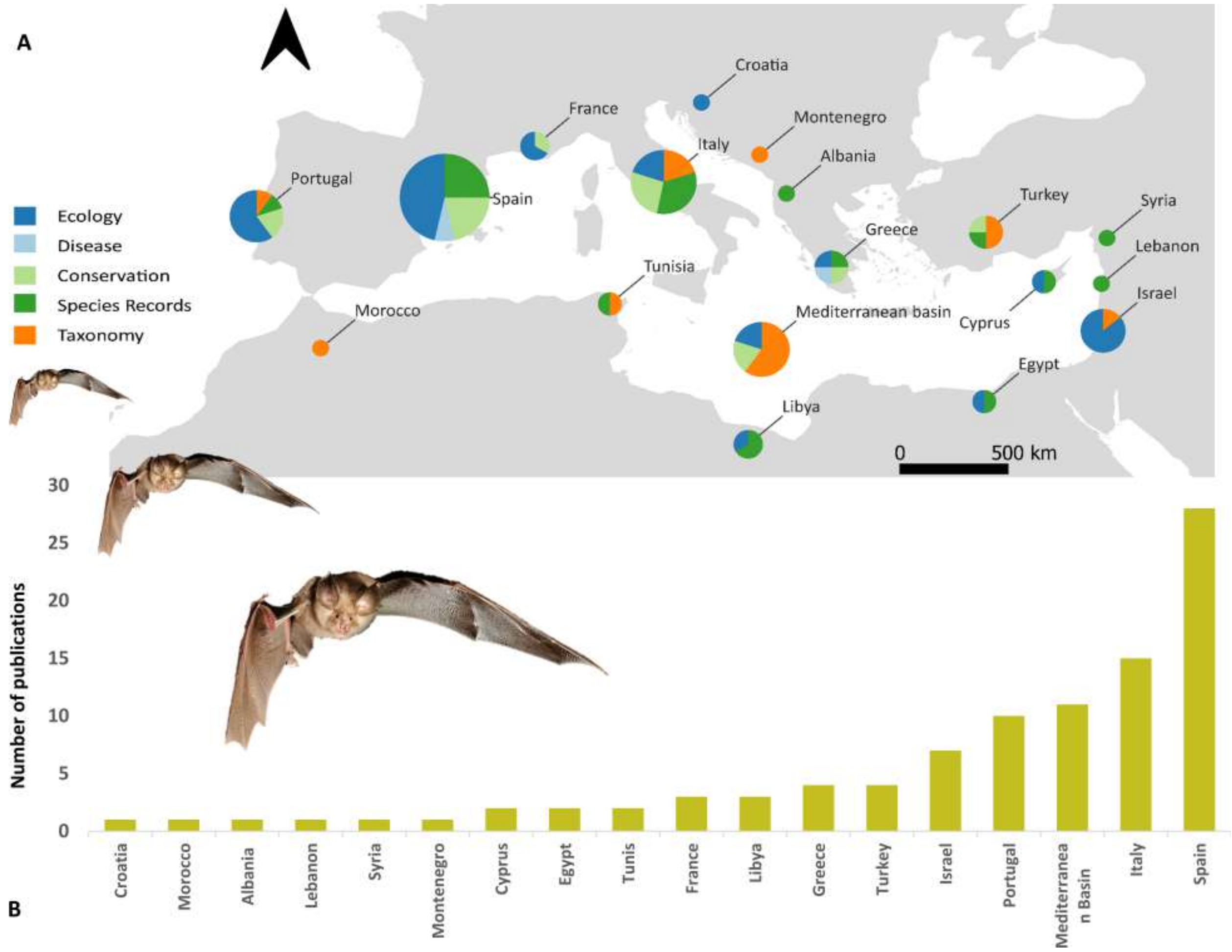

Figure 5 – A: Map showing the geographical distribution of the studies per research thematic topics across the Mediterranean countries (map was created using Quantum GIS 3.04 “diagram” function). B: Bar plot showing the number of published papers by country. The "Mediterranean basin" designate studies conducted across multiple countries.

Discussion

Research topic trends

Since the twenty-first century, bat conservation has become a top global priority, and the need to confront and limit all threatening factors has become critically essential (Frick et al., 2019). In this regard, a significant worldwide increase in the number of studies, culminating in the publication of thousands of papers and reports, paves the way for further research patterns regarding bat taxonomy, status, diversity, ecological role, and diseases. Given that, our review findings confirmed the rise of the number of publications covering a diverse range of research scope related to the Mediterranean bats population over the last years. This increase is highly attributed to a variety of factors, including the advancement of monitoring techniques, and the provision of adequate funds and research grants, as well as the need to enhance our evidence on these species.

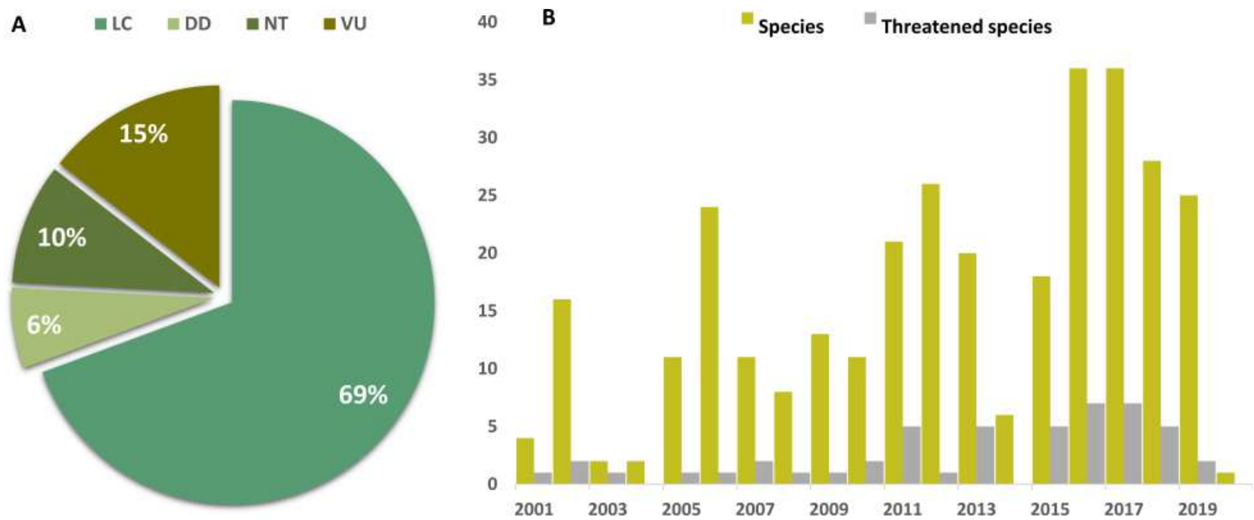

Figure 6 – General distribution and trends of Mediterranean bat research over between 2000 and 2021. A: Pie chart showing the percentage of Mediterranean bats in each red list category based on their conservation status indexed by IUCN (2021); data deficiency (DD), least concern (LC), near threatened (NT), vulnerable (VU). B: Number of cited threatened and total species over the years.

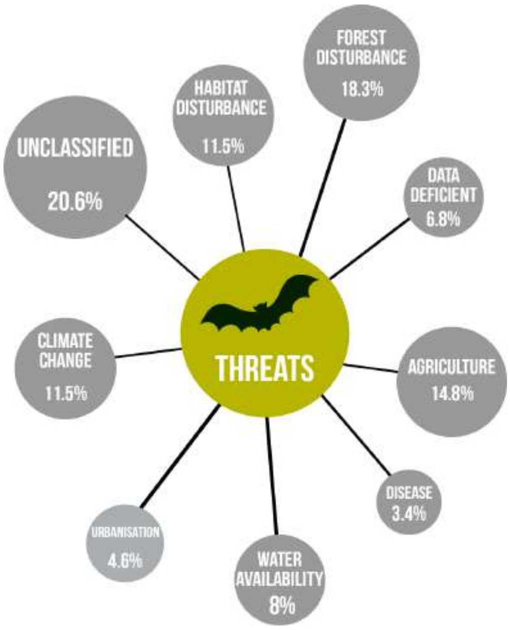

Figure 7 – Scheme showing the main threats factors affecting Mediterranean bats, as cited by authors.

Ecology

Although the expansion in the number of publications in recent years, papers were unevenly distributed across the various thematic research topics. Our findings revealed that more than a third of the examined publications were devoted to research related to ecological aspects. The percentage of ecological research papers was significantly greater than that found in related reviews conducted by Tanalgo and Hughes (2018) in Philippines and by Feijo et al. (2019) in China, and was somehow similar to the findings of the review conducted by Preble et al. (2021) in Japan. This bias in studying the ecology could be due to the need and demand to quantify and evaluate the role of bats in the ecosystem, especially as a large portion of the Mediterranean shift to more sustainable agriculture. In our case, and since most of bats are insectivores, research mainly highlighted bats for their role as insect prey predators rather than their pollination or seed dispersing aspects.

In Spain, Puig-Montserrat et al. (2015) estimated the economic benefits of bats at around 22.5 Euro/ha per year. This result was consistent with several studies conducted in various agricultural fields around the world, such as cornfields and rice fields in Thailand (Wanger et al., 2014), vineyards in France (Charbonnier et al., 2021), enlightening the economic benefits of bats as a pest controller. Bats were also been praised for their ability to improve crop yields in cotton fields (Korine et al., 2019), vineyards (Froidevaux et al., 2017), and olive groves (Davy et al., 2007).

However, several studies have found that bat ecological roles vary across habitats and could be affected by environmental factors. For instance, Herrera et al. (2015) discovered that bats had a higher ecosystem contribution in organic agricultural areas compared to conventional agricultural sites. Rainho et al. (2010) demonstrated the difference in bat foraging activity between cluttered and uncluttered forests. While Napal et al. (2013) illustrated the influence of deforestation on bat ecosystem services. On the other side, as the presence of a frugivorous bat was particularly intriguing and spatially restricted to certain areas, several studies validated their role across the basin. In Cyprus, Del Vaglio et al. (2011) emphasized *Rousettus aegyptiacus* negative impact on fruit orchards while ignoring their essential role as natural pollinators and seed dispersers. On the other hand, Hadjisterkotis (2006) highlighted the positive contributions of *Rousettus aegyptiacus* through eating only ripe fruits, resulting in a decrease in fungi and a destructive pest population. Additional quantitative data on bat insect preferences in various vegetation habitats, as well as a better understanding of bat insect suppression, pollination, and seed-dispersal roles, are needed.

Bat diseases

Studies focusing on bat diseases and ectoparasites are still considered very scarce across the basin. Only three studies were related to bat diseases. The earliest research discovered the presence of Lyssavirus in the Spanish bat population by Serra-Cobo et al. (2010). After a while, Stekolnikov and Quetglas (2019) reported a new bat parasite known as trombiculids for the first time in Spain. This limited number of studies may be directly tied to public perceptions of bats, which always posed a challenge to bat conservation, especially following the association of bats with the SARS virus in 2002 (Li et al., 2005). However, social disdain and additional persecution on bats population are likely to increase, particularly following the recent pandemic (Covid-19), for which bats were accused of (Macfarlane and Rocha, 2020). Research on disease-relevant bats, on the other hand, is expected to increase in order to prevent future unforeseen outbreaks (Lu et al., 2021). Given bats' unpopularity in society and their association with zoonotic disease, future research must subtlety consider the negative consequences in order to avoid further harm, similar to the recent testimonies of planned bat killings carried out by local communities in Peru (Durán, 2020), India (Goyal et al., 2021), Australia (Lentini et al., 2020), and Indonesia (Tsang, 2020).

Taxonomy and species records

Over the last 15 years, a particular increase in bat species descriptions was distinguished and has outpaced that of other mammalian species by more than 25% (Burgin et al., 2018). This could highlight the importance of taxonomic research, which is currently regarded as a powerful technique for identifying new world species and subspecies (Tsang et al., 2016). On the local level, a paradigm shift in the taxonomic knowledge of bat species found in the region was noticed especially after the series of taxonomic and checklist reviews across the Mediterranean countries carried out by Benda et al. in the last 15 years (Benda et al., 2003, 2006, 2008, 2010).

As part of taxonomic methodologies, molecular studies have revealed an unexpectedly high diversity of cryptic lineages among bats worldwide, including Europe (Bogdanowicz et al., 2015; Mayer and von Helversen, 2001). Our study highlighted the importance of taxonomic research in identifying new cryptic species, which were previously thought to be the same. Several Mediterranean bat species were lately identified including: *Plecotus sardus*, endemic species in Sardinia (Mucedda et al., 2002), and *Plecotus kolombatovici*, which has also been reported recently by Ancillotto et al. (2019a) in Italy. Also, the Maghrebian Mouse-eared bat, which was known as *Myotis blythii*, was later on designated as a separate species called *Myotis punicus*. Moreover, the encouraging findings of Ibáñez et al. (2006) in the Iberian Peninsula, which confirm the existence of more than 20% of the bat population with cryptic lineages, have opened the door and prompted other researchers to delve deeper into Mediterranean bat species taxonomy. In 2011, Trujillo and Gonzalez discovered the presence of new species *Pipistrellus maderensis* which is endemic to Madeira, Azores, and the Canary Islands. One year later, Puechmaille et al. (2012) used genetic differences to identify cryptic lineages within the *Myotis nattereri* species complex. Also, Puechmaille et al. (2014) discovered a new species, *Miniopterus maghrebensis sp. nova*, which was previously known as *Miniopterus schreibersii*. Recently Juste et al. (2018) discovered two new *Myotis nattereri* cryptic bat species using mitochondrial and nuclear DNA sequencing. This continued rise of new species discovery can be a hindrance to conservation as it's difficult to determine the status of newly identified species in a short period of time (Tsang et al., 2016). Therefore, more accurate research are needed to identify and conserve newly discovered species that have been excluded for years and could have been exposed to unanticipated ecological consequences and threats.

Applied methods

A wide range of methods and approaches was employed to monitor bat presence, estimate their population sizes and distribution, under-

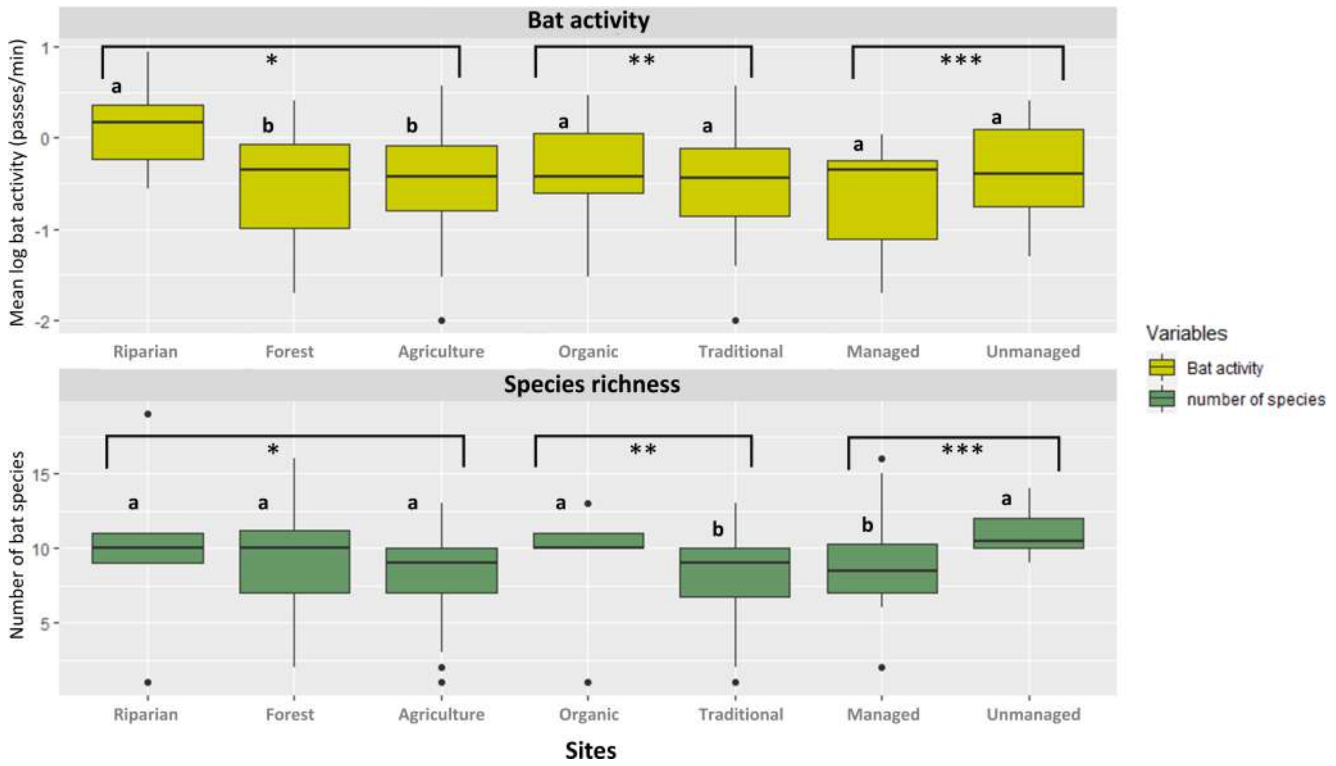

Figure 8 – Box plots representing the variation of mean log bat activity (passes /min) and species richness (number of bat species) in relation to different type of habitats (*) (agriculture, forest and riparian areas) and land management: (**) agricultural practices (organic vs traditional) and (***) forest managements (managed vs unmanaged) found in the 18 quantitative papers.

stand their foraging, dietary and migratory behaviour, and assess their ecological attributions in addition to their interaction with the environmental factors. However, when assessed, acoustic monitoring, DNA analysis, radio-tracking, and morphological analysis were found to be more commonly used.

Our results showed dominance in using acoustic monitoring methods with more than a third of studies. Although these method require considerable time and effort and are considered labour-intensive techniques and could be challenging when to analysis data of passive monitoring particularly for species with quite calls. Acoustic monitoring popularity, can be attributed to their ability to provide accurate, robust data on bat population and abundance (Russo and Voigt, 2016). These techniques are expected to become widely used as additional affordable bat detectors are becoming available such as AudioMoth (Hill et al., 2019). However, adopted methods are usually strongly related to the research's aim. Although the majority of research has been focused on the ecological role and taxonomic aspects of bats, methods such as stable isotopes have been found to be less adapted despite their potential in understanding bat feeding strategy (Herrera et al., 2008) and uncovering bat subtle ecological conditions (Cryan et al., 2012). Though less commonly used methods, such as modelling techniques, must be adopted more frequently in future conservation implementations, particularly since it provides a powerful tool for projecting upcoming threats and conservation challenges (Barros et al., 2021; Razgour et al., 2016; Lison and Calvo, 2013; Bilgin et al., 2012; Rebelo et al., 2010). Hence, an unbiased adaptation of methods will elucidate an understandable and unhindered research spectrum on Mediterranean bats.

Geographical research distribution

Our review showed a geographical bias in the research effort. The majority of studies were conducted in European countries, particularly Spain and Italy, whereas less research were published in Asian and African countries. This spatial bias may be related to the fact that European countries cover the largest area of the basin and have more protected natural areas and forest areas, which have served as study sites for several studies, such as Goiti et al. (2004) in Spain (Urdaibai Biosphere Reserve) and Lino et al. (2014) in Portugal. Furthermore, the observed geographical bias may be related to the fact that African and Asian nations are perceived to be less environmentally conscious compared to European nations in addition to the financial limitations that may hamper local scientific evolutions. Nonetheless, the EU-drafted Convention recommendations have encouraged European countries to take immediate action to conserve bats, through conducting additional scientific research efforts to reach conservation goals set by local and EU conventions (Voigt and Kingston, 2016).

Additional collaboration with local researchers, particularly in understudied areas, is strongly encouraged and could play an important role in exchanging research expertise and methodology, as well as increasing conservation and informative research evidences to fill the gap in research efforts across different Mediterranean countries.

Species diversity and taxonomic bias

In our review, 61 species were cited in the 97 studied articles. When compared to global data, Mediterranean bat diversity appears to be less diverse than China (135 species) (Feijo et al., 2019), Indonesia (221 species) (Maryanto et al., 2019), Colombia (187 species) (Solari et al., 2013), and Peru (165 species) (Pacheco et al., 2009). Although its small geographical range, the Mediterranean basin appears to encounter a more diverse bat population than larger areas like North America (49 species) (Harvey et al., 2011) and Europe (51 species) (Dietz et al., 2009). This could be due to the Mediterranean's role as a transcontinental location, the variety habitats present, as well as the availability of water resources, particularly on the European side of the basin, which is thought to be critical for bat survival (Dietz et al., 2009).

Taxonomic bias is still an issue in conservation research since it contradicts research recommendations and leads to the marginalization of many species (Tsang et al., 2016). Unfortunately, we discovered a taxonomic bias at two distinct levels in our review. Firstly and despite being accounted for 21% of the total Mediterranean bat population, threatened bats have received far less attention than non-threatened bats. This research inequality may be directly related to the population decline of threatened bats, as well as monitoring challenges since they are classified as forest or cave bats and may be difficult to reach in many cases (Leal and Bernard, 2021). Secondly, a taxonomic bias was observed between species and family research efforts. The most cited species were bats belonging to the Vespertilionidae family, which could logically be attributed to the fact that most of the Mediterranean species population belongs to this family.

Remarkably, some species were only mentioned once, which could raise concerns and could potentially posing additional threats to their presence in the basin. However, more research on less studied and near-threatened species is urgently needed to fill the gaps to address the pervasive lack of data to improve our understanding of these species.

Conservation and main threats

Several anthropogenic and environmental threats continue to imperil Mediterranean bats (Voigt and Kingston, 2016). Forest disturbance was identified as the most devastating threat, causing the deterioration of roosting and foraging sites, particularly by removing old and dead trees (Russo et al., 2016) and unsustainable silvicultural practices (Law et al., 2016). Hence, to counteract such threats, many silvicultural strategies were generated, with bat conservation as a main priority (Law et al., 2016). Bats, as predicted, appeared to be extremely sensitive to environmental changes. Climate change was also identified as a serious threat in different studies, affecting bats' ecophysiology, hibernation, the reproduction cycle activity (Ancillotto et al., 2018). Water pollution is considered to be a perilous factor that could harm bat populations, especially those who depend on surface water for drinking or foraging (Rainho, 2007). Bats are also threatened by the overuse of chemical pesticides, which not only causes a decline in insect population but also affects bat health by bio-accumulating in their tissues (Puig-Montserrat et al., 2015). Wind turbines have been found to have a significant impact on seasonal bat migratory species and mating patterns, and a large number of bat fatalities have been recorded in wind farms across the Mediterranean, including Italy (Ferri et al., 2016) and Spain (Muñoz and Farfán, 2020).

Threats appear to differ across continents and to be dependent on culture, ecosystem, and human factors. In East Asia, for instance, illegal bat hunting for food trading is regarded as a one of the major threat (Mildenstein et al., 2016). Heatwaves and wind energy have been identified as the primary threats to bat survival in Australia (O'Shea et al., 2016), whereas in the northern hemisphere, the emergence of an infectious fungal disease of bats, white-nose syndrome (WNS), has resulted in millions of bat deaths (Grieneisen et al., 2015). To date, fortunately these threats appear to have little impact on Mediterranean bats. However, in some parts of the Mediterranean region, some species are still hunted for traditional folk medicinal purposes (Riccucci, 2012).

Despite the primary concern and critical need for global bat safeguarding, conservation efforts have stalled over the last 20 years. This conservation effort is undoubtedly influenced by the low number of papers, insufficient legal protection framework, an inability to enforce protection laws, and a failure to implement sustainable agricultural, forestry, and building restoration practices (Frick et al., 2019). Hence and in the face of impending threats, legislative and practical conservation measures are required, with a strong emphasis on increasing the number of publications addressing particularly threatened species as a priority in any future conservation studies (Browning et al., 2021; Russo and Jones, 2003).

Bat activity, and richness across habitats and land management

Our categorical quantitative comparisons revealed the effect of different habitat types and systems on bat activity and species richness. Although species diversity did not differ, bat activity revealed a consistent difference among the three habitats types. Riparian areas appeared as the preferred habitat for bat foraging. Indeed, this habitat preference could be directly related not only to the direct fact of the presence water resource but also due to the availability of a higher number of insects that usually emerge near water (Fonderflick et al., 2015), particularly during the summer season (Salvarina, 2016). Our findings were consistent with other Mediterranean studies that highlighted the importance of riparian areas as foraging sites. Higher bat activity was recorded in riparian areas compared to forest and agricultural areas in Italy (Di Salvo et al., 2010; Russo and Jones, 2003), Portugal (Amorim et al., 2018; Mendes et al., 2014; Rebelo and Rainho, 2009; Rainho, 2007), and Spain (Mendes et al., 2014; Puig-Montserrat et al., 2015; Lison and Calvo, 2011). According to Lison and Calvo (2014), water ponds in Mediterranean forests have higher bat activity and diversity than adjacent forest matrix areas. It was also found that permanent water bodies and riparian areas can significantly influence bat species assemblages and activity (Razgour et al., 2011; Rainho, 2007; Russo and Jones, 2003). Similarly, artificial water sources near foraging areas, such as irrigation ponds and dams, was found to have a positive effect on prey abundance (Ancillotto et al., 2019b; Sirami et al., 2013). Nonetheless, Korine et al. (2015) demonstrated that the quality of the water has a critical impact on bat activity and species richness.

Over the last two decades, the expansion of intensive agriculture and the overuse of chemical pesticides in Mediterranean regions has had a significant negative impact on bat richness and activity, as well as insect population (Kolkert et al., 2020). Bats were found more active in organic fields than in conventional fields, most likely due to the negative relationship between agrochemical inputs from one side and insect population and bat activity from the other side (Rodriguez-San Pedro et al., 2018). Our findings strengthened the potential impact of organic agriculture on bat richness and activity and were consistent with previous results (Froidevaux et al., 2017; Toffoli, 2016; Herrera et al., 2015; Davy et al., 2007).

Currently, several forest management strategies are adapted across the Mediterranean forests. Based on our statistical approach, bats were found more active in managed forests than in unmanaged areas. For instance, Charbonnier et al. (2014) explained similar findings by linking this preference to an increase in insect population following forest management practices such as clear-cutting and thinning. However, it is hypothesized that bat response to forest management tends to vary upon species foraging habits. Morris et al. (2010) discovered that forest management has a positive impact on the activity of foraging species in open and edge habitats. Ancillotto et al. (2021) recently concluded that forest management negatively affected clutter-adapted species activity, potentially resulting in the loss of this species foraging sites. More sustainable forest management, particularly those that promote heterogeneity in forest age and structure and retain old trees and snags, is suggested as a way to improve and conserve Mediterranean bat's habitats and foraging sites (Russo et al., 2016; Lison and Calvo, 2014).

Conclusions

The current review describes the bat status and conservation challenges across the Mediterranean basin, as well as research priorities and gaps. Although the increase in the number of researches throughout the year, this number is still insufficient since bats are facing some serious threat. In addition to the limited number of research devoted to threatened species. Our findings indicate a bias toward certain geographical areas and thematic research, as well as a significant species preference. As predicted, our quantitative findings showed that habitat characteristics, as well as forest and agricultural practices commonly found throughout the basin, have a strong influence on bat population activity and species assemblage.

Our review will serve as a basis for future research in the basin. However, several measures are recommended to close current knowledge gaps and implement more effective future conservation: (1) Multinational collaboration among Mediterranean countries in law enforcement and additional research cooperation. (2) To place a greater emphasis on understudied areas, particularly in the African and Asian parts of the Mediterranean. (3) For more effective conservation, more research on threatened and newly recognized species is also required. (4) Carry out additional studies in disease and conservation-related thematic research areas. (5) Improve the legal framework's implementation. (6) Encouragement of sustainable agricultural and forestry practices. (7) Increase the number of research and studies focusing on Mediterranean bats in all thematic and geographical areas in an unbiased manner.

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Associate Editor: L. Ancillotto